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Radiation Resistant HTS Quadrupoles for RIA

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***Abstract*—Extremely high radiation, levels with accumulated doses comparable to those in nuclear reactors than in accelerators, and very high heat loads (~15 kW) make the quadrupole magnets in the fragment separator one of the most challenging elements of the proposed Rare Isotope Accelerator (RIA). Removing large heat loads, protecting the superconducting coils against quenching, the long term survivability of magnet components, and in particular, insulation that can retain its functionality in such a harsh environment, are the major challenges associated with such magnets. A magnet design based on commercially available high temperature superconductor (HTS) and stainless steel tape insulation has been developed. HTS will efficiently remove these large heat loads and stainless steel can tolerate these large radiation doses. Construction of a model magnet has been started with several coils already built and tested. This paper presents the basic magnet design, results of the coil tests, the status and the future plans. In addition, preliminary results of radiation calculations are also presented.**

***Index Terms*—High-Temperature Superconductor, HTS magnets, radiation resistant magnets, Rare Isotope Accelerator.**

I. Introduction

The Rare Isotope Accelerator [1,2] is a proposed major facility in United States for research in Nuclear Science. It will produce copious amounts of rare isotopes when a high-energy heavy ion beam hits the target. The Fragment Separator [3] will then select a particular isotope and transport it to an experimental area. For optimal capture efficiency, superconducting magnets are required in at least the first focusing quadrupole triplet of the separator. These magnets are one of the most challenging elements in the RIA proposal, as they are exposed to several orders of magnitude more radiation and energy deposition than typical beam line and accelerator magnets receive during their entire lifetime [4]. The first quadrupole itself is subjected to ~15 kW of energy deposition.

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We propose a super-ferric warm iron magnet design based on commercially available High Temperature Superconductors (HTS). The use of HTS allows the magnet to operate at 20-40 K temperature for efficient heat removal. The lifetime dose of high-energy (several hundred MeV) neutrons on this quadrupole has been crudely estimated and confirmed with radiation transport calculations to be 10^{19} neutrons/cm^2. At such a high radiation dose, the integrity of various magnet components, like the insulation, may fail. The organic insulation that is used in present accelerator magnets will not survive these radiation doses. We plan to use stainless steel tape, that being a metal, is a robust radiation resistant insulation. As a part of this R&D program, the influence of high-energy neutrons on HTS will be experimentally measured to determine the maximum acceptable dose.

II. Overview of the Magnet R&D Program

As the RIA project is in its early stages, the beam optics of the fragment separator region is still evolving. These iterations have changed the aperture and the location of the quadrupole magnets. In this paper, we report magnet designs of 100 mm and 280 mm apertures. Both designs are based on commercially available HTS tape. As a part of this program, we have purchased over 3 km (with a minimum piece length of 220 meter) of high strength BSCCO 2223 conductor from American Superconductor Corp. [5].

The magnet R&D program has been developed to match the available and expected funding profile while testing the key components of the design at several stages along the way. The current design requires 24 coils in a completed magnet. In this multi-stage program, we will test each pair of coils in liquid nitrogen at 77 K (or a lower temperature by adjusting the nitrogen pressure). The initial few coils and a few other coils made during the later production will also be tested at 4 K in liquid helium. In addition, some coils will be tested at 20-30 K. The first six coils will be tested in a magnetic mirror configuration to establish the key parameters of the magnet design. Another major milestone will be the test of 12 coils (half magnet) in its own cryostat where the operating temperature can be varied. At this stage, we also plan to study the influence of a simulated heat load. The first phase of the model magnet program would be completed with the test of the completed magnet with 24 coils. In parallel, the influence of radiation damage on HTS and other components will be examined. The above program will establish the feasibility and benefits of using HTS in the fragment separator of RIA.

III. MAGNET DESIGNS

We have studied quadrupole designs to meet several aperture and gradient requirements. In this paper, however, we limit our discussion to two designs.

A. *Quadrupole design for 100 mm Aperture*

The initial optical design [6] required a good field aperture of 100 mm and a gradient of 32 T/m. The first magnet appears soon after (300 mm) the production target. The angular distribution of the neutron spectrum from the production target is highly anisotropic and contains a strong forward angle peak. A typical neutron distribution [7] of the neutron yield (Xenon with 400 MeV/nucleon) as a function of solid angle away from the target is shown in Fig. 1. We achieve about an order of magnitude reduction in radiation dose by placing the coil outward (see Fig. 2) rather than placing them at a similar radial location where the iron pole is.

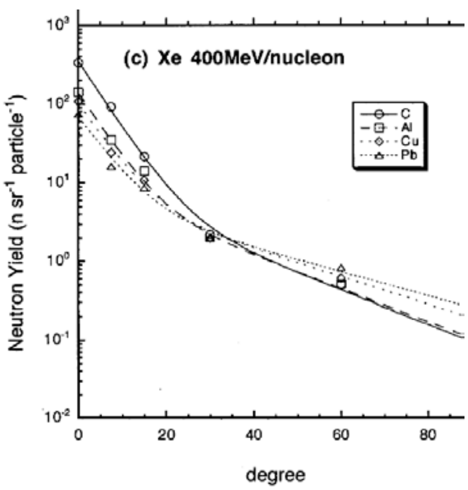

Fig. 1. Neutron yield as a function of solid angle [7]. The large drop as a function of angle indicates the benefit of developing designs where the coils are placed away from the magnet center.

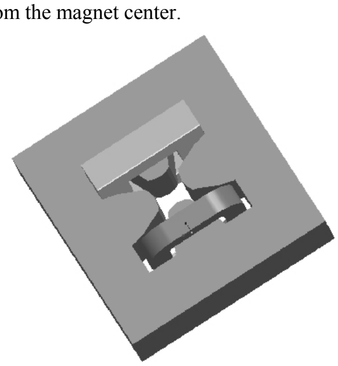

Fig. 2 The warm iron super-ferric quadrupole design for RIA. The two racetrack coils produce quadrupole symmetry in the cross section. The upper coil is rendered in its own cryostat and the lower coil is not. The coils are placed away from the magnet center to reduce the radiation dose.

In this super-ferric magnet design, the magnetic flux is funneled through the iron yoke to obtain a pole tip field that produces the desired gradient of 32 T/m. The pole tip is at a radius of 55 mm. A large reduction in the radiation induced heat load (from ~15 kW to ~130 W) is achieved by adopting a warm iron design. To reduce the cold volume in the magnet ends and to simplify the coil design so that the magnet uses simple racetrack coils, we adopt a symmetric two-coil design (see Fig. 2) that has quadrupole symmetry in the 2-d cross section and dipole symmetry in the ends. The overall magnet design will be optimized so that it has net quadrupole symmetry in an integral sense and meets the field quality requirement. The field quality requirements are not expected to be stringent (few parts in thousand or worse) as this is a beam line magnet. A preliminary engineering design of the magnet with cryostat is shown in Fig. 2. Since the new optics requires a much larger aperture magnet, we did not carry this design study further and did not build coils based on this design.

B. *Quadrupole design for 280 mm Aperture*

The newer optics increased the good field aperture requirement from 100 mm to 280 mm and decreased the gradient from 32 T/m to 10 T/m. Since these parameters are significantly different from the initial proposal, we decided to develop a new design before the magnet construction began. The specified effective magnetic length is 1 meter.

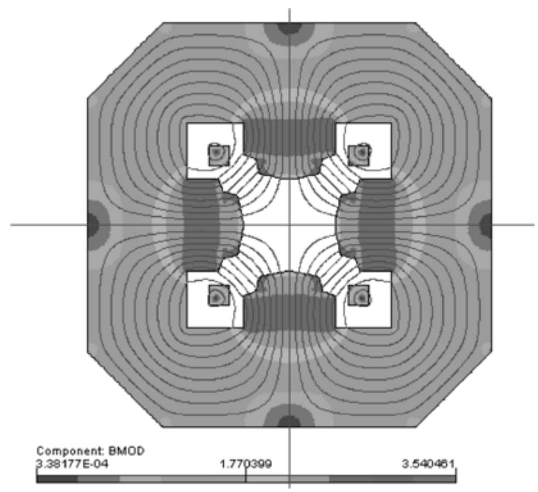

Fig. 3. An OPERA2d model of the 280 mm aperture super-ferric quadrupole design for RIA with field lines and field intensity in coil and iron regions. The above model shows the complete magnet; however, most of the 2-d calculations were made using an octant of the above model by taking advantage of the quadrupole symmetry.

An OPERA2d [8] model of the magnet is shown in Fig. 3. The iron in the pole area is shaped to optimize field quality and to enhance the field at the pole tip. Sufficient space in the design is left for a warm cryostat. A crucial part of engineering this warm iron design is the development of a compact cryostat that can efficiently remove over 100 Watts of heat from the HTS coils at 20-30 K. The complete magnet contains 24 coils, each having 175 turns. The overall cross section is 62 mm X 62 mm. The required gradient is reached at 125 A.

An OPERA3d model of this design is shown in Fig. 4. As in the case of the 100 mm aperture design, we use two coils to minimize the cold volume at the magnet end. The coils create a quadrupole symmetry in the magnet cross-section.

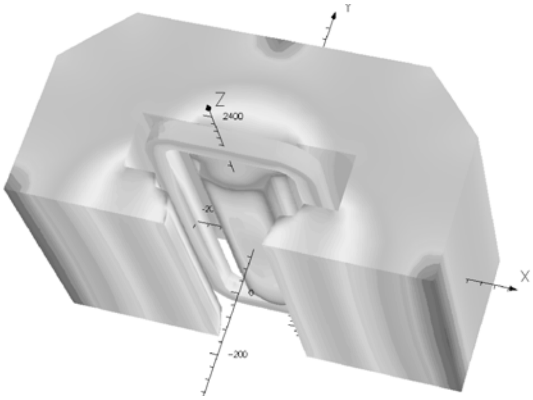

Fig. 4. An OPERA3d model of the 280 mm aperture super-ferric quadrupole design for RIA. Color indicates the field intensity on the surface of coil and iron regions. The above model shows only one symmetric half the complete magnet. The magnet is being designed to have quadrupole symmetry in the integral sense and as well as a quadrupole symmetry in the magnet cross-section.

C. *Magnetic Mirror design for the Quadrupole*

As a part of our staged R&D effort, we are initially building a magnetic mirror configuration of the above design that uses six coils instead of twenty-four. In this case, a magnetic iron mirror is placed where the field lines are perpendicular (see Fig. 3). A 3-d model of the magnetic design is shown in Fig. 5. The length of the coil is chosen to be 300 mm, in part to minimize the modifications required in the local test facility.

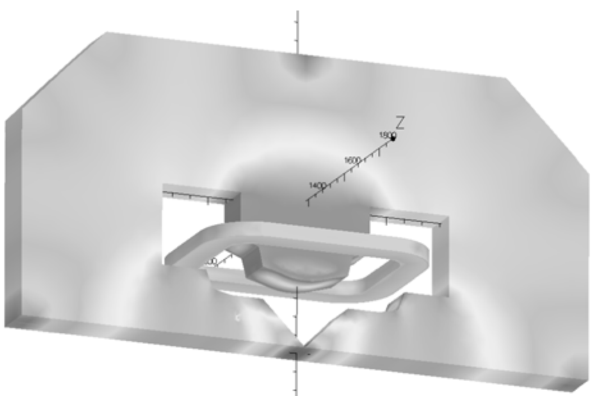

Fig. 5. An OPERA3d model of the magnetic mirror design. Color indicates the field intensity on the surface of coil and iron regions.

IV. Magnet Construction

The 175-turn coil is made by co-winding HTS tape and stainless steel tape that will serve the role of radiation resistant insulator (see Fig. 6). Several clamps are used during the coil winding to keep the turn-to-turn spacing minimum and uniform. HTS tape has a nominal thickness of 0.31 mm and nominal width 4.2 mm whereas the stainless steel insulating tape has a nominal thickness of 0.04 mm and nominal width 4.6 mm. High strength HTS tape has a stainless steel backing on either side that increases the thickness by ~0.1 mm and thus reduces the effective current density by ~50%. However, we accept this penalty in favor of a more robust and reliable construction, as the high strength HTS tape is much less prone to damage during winding. Each coil uses ~215 m of tape.

The overall dimension of the racetrack coil is 300 mm X 504 mm with a minimum bend radius of 50.8 mm. Each coil is wound separately as a single pancake coil. The coils are connected together with five perpendicular jumpers (splices) using HTS tapes that do not have stainless steel backing on either side. The splices are made using indium solder. The stainless steel backing tape is not removed from the part of HTS tape that is in the coil. Previously, the joint resistance of similar splices was studied [9]. The joint resistance decreases linearly with the number of jumpers and with five jumpers it will be below 0.7 micro-ohms at 77 K. The insulation between coils will be either a ceramic sheet or a ceramic coating on either side of a thin stainless steel spacer.

A simple structure consisting of a non-magnetic insert and non-magnetic external support plates has been developed for testing a pair of coils in liquid nitrogen and liquid helium. A detailed engineering design of the magnetic mirror configuration and for the complete magnet is currently being developed.

Fig. 6. A coil is being made by co-winding HTS tape (on right) and stainless steel insulating tape (left).

V. Test Results

A pair of coils has been tested in liquid nitrogen (77 K) and in liquid helium (4 K). The test configuration is such that the two coils can be powered together or individually. We plot the voltage gradient (a measure of effective resistance) across each of the coils as a function of current at 77 K (Fig. 7) and at 4 K (Fig. 8). The measured “critical” currents (in Amperes) are given in Table I at the field generated by coil themselves. We report currents for an average gradient of 0.1 μV/cm (more relevant to accelerator magnet operation) and for the 1 μV/cm (industry standard). The numbers in Table I at 4.2 K for 1 μV/cm definition are obtained by linear extrapolation of the data on a log(V) vs. current plot. The critical current specification for the HTS tape was 100 A (for 1 μV/cm) at 77K and zero field, i.e., $I_c(77K,0T) = 100A$. For comparing the measurements to the expected values, the critical current must be scaled to the appropriate field, field direction and temperature [5]. The maximum magnetic field (self-field on the coil surface) at 100 A when an individual coil is powered is 0.3 T and when a pair coils are powered in series is 0.5 T. The self-field scales linearly with current since no magnetic material is used in test structure. The measured coil performance implies that there was no noticeable degradation in conductor performance during the coil fabrication process.

TABLE I
MEASURED CRITICAL CURRENTS (A) IN THE SELF-FIELD OF THE COIL(S)

	Coil 1 (alone)	*Coil 2 (alone)*	*Coil 1 (with coil2)*	*Coil 2 (with coil1)*
I_c(0.1 μV/cm, 77K)	53	54	41.8	42.2
I_c(1 μV/cm, 77K)	62	65	50.5	51.5
I_c(0.1 μV/cm, 4.2 K)	419	433	364	372
I_c(1 μV/cm, 4.2 K)	443	463	384	398

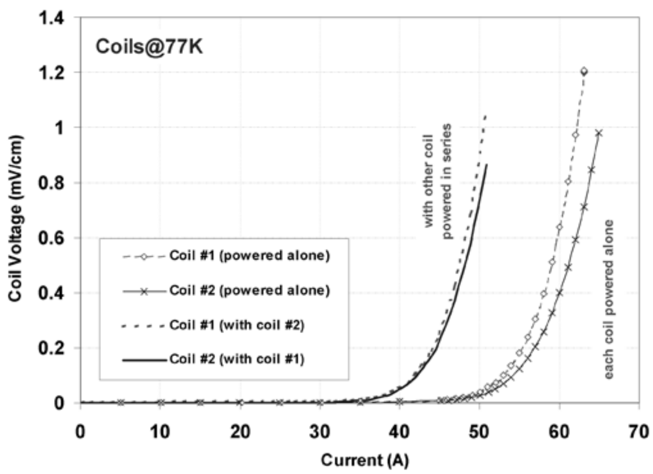

Fig. 7. Measured coil performance at 77 K when powered alone and when powered together in series.

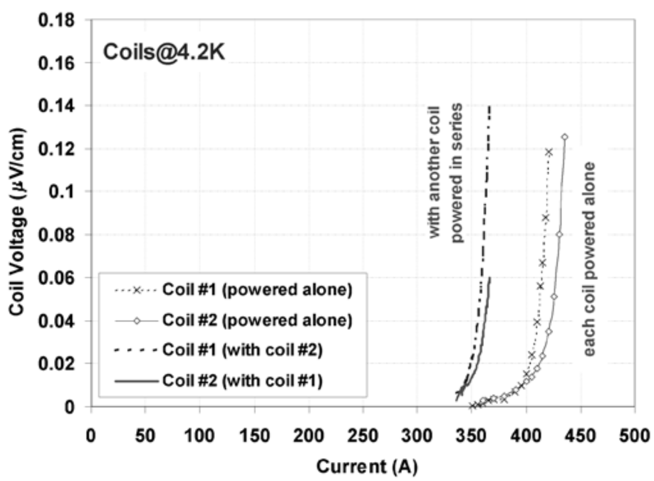

Fig. 8. Measured coil performance at 4.2 K when powered alone and when powered together in series.

VI. RADIATION CALCULATIONS

The first quadrupole magnet in the RIA Fragment Separator (FS) is subject to considerable radiation from the production target. The beam will lose 20-50% of 400 kW (maximum beam power) in the production target located directly in front of the first quadrupole, resulting in copious amounts of penetrating radiation directed at this magnet. The magnet design used in the radiation dose calculation has a pole at a radial location of 100 mm. Radiation transport calculations were done with the Monte Carlo code PHITS [10].

The coil material was taken as pure silver, so the addition of lighter elements changes the results slightly, but the likely increase will not be much. No insulation is used in the coil calculations; the separation between the coil and the magnet iron was taken as a vacuum. The truncated cone between the target and the coils is the tungsten (the main constituent of machinable Hevimet) shadow shield. The shield is 2.25 metric tons. The model calculations show that the tungsten shield is subjected to a heat load of 28 mW/cm^3 (total load 3.3 kW), iron 25.3 mW/cm^3 (total load 9 kW), and HTS coils 5.1 mW/cm^3 (total load 135 W). This clearly shows the benefits of a warm iron design.

One major concern is the neutron flux. More data is needed to determine the acceptable dose of high-energy neutrons on HTS coils. Calculations that need to be done are ones using the newest geometry, where the pole tip radius is approximately 145 mm. In addition, magnetic fields, more cryostat and support structure and the actual composition of the conductor will need to be added to the calculations.

VII. CONCLUSION

HTS magnets with stainless steel tape insulation offer an efficient solution to the challenges posed by the extremely large radiation and heat loads in RIA. However, this technology has never been used in particle accelerators and hence needs to be demonstrated with a few years of significant R&D effort. If successful, it offers a unique technology for radiation resistant superconducting magnets that can tolerate high heat load loads.

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